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**A REVIEW ON MINERALOGY ANALYSIS OF PULVERIZED COAL BY
QEMSCAN WITH AN EMPHASIS ON MINERAL ASSOCIATIONS AND
ASH IMPACTS**

TECHNICAL NOTE 30

Authors:

**Yinghui Liu
Rajender Gupta
Terry Wall**

The University of Newcastle

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QCAT Technology Transfer Centre, Technology Court
Pullenvale Qld 4069 AUSTRALIA
Telephone (07) 3871 4400 Facsimile (07) 3871 4444
Email: Administration@ccsd.biz

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Curtin University of Technology	Prof Linda Kristjanson
Macquarie University	Prof Jim Piper
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**Cooperative Research Centre for
Coal in Sustainable Development**
 QCAT Technology Transfer Centre
 Technology Court
 Pullenvale, Qld 4069
 Telephone: (07) 3871 4400
 Fax: (07) 3871 4444

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AUTHORS: **Y. LIU, R. GUPTA, T. WALL**

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Summary

The objective of CCSD Project 2.2 is to assess the qualities of pulverized coal used for power generation. The characteristics of ash forming inorganic matters in coal are critical for evaluation the coal ash impacts in a pulverized-coal power station. The ash residue formed from combustion processes gives rise to slagging, fouling, erosion, corrosion, and fine particulate matter emission in power stations thus increases maintain cost, operational risks and environmental impacts.

Ash is formed from mineral matter in coal by complicated physical and chemical mechanisms. Although there have been many studies on ash formation and ash impacts on power generation there is little detailed data on mineral matter in pulverized coals due to absence of perfect analytical mineral characterization tool and complicity of occurrence of mineral matter in pulverized coal. Thus Project 2.2.4 was aimed to develop the capabilities of QEMSCAN to characterize mineral matter in pulverized coal in terms of mineralogy composition, chemistry composition, size, shape, included/excluded association and mineral-mineral association.

Conventional and advanced mineralogy analysis tools have been reviewed and compared. It is concluded that CCSEM-type techniques are the best techniques for they provide information determining transformation of mineral matter to ash and ash impacts in combustion system.

With continuous development in sample preparation technique, instrument updates and data post-processing and interpretation, QEMSCAN has been proved capable of providing information on diverse aspects of mineral matter in coal, some of them are first observed by QEMSCAN, i.e. mineral-mineral association. The information obtained from QEMSCAN has helped to establish a better understanding of mineral matter in coal and their transformation during combustion thus the impact on combustion systems. The current status of QEMSCAN is that it has been calibrated for several major commonly occurring minerals in coal, however if there is a unusual mineral present in the sample it needs further calibration; furthermore some current mineral species may need refine if natural occurring minerals have chemical composition significantly differing from theoretical stoichiometric composition; interpretation of QEMSCAN data requires expertise knowledge in corresponding fields.

Currently QEMSCAN analysis can be interpreted to predict ash impacts in pf furnaces by two methods, observation of QEMSCAN images and comparison of coals by statistical means, and prediction after conversion to an equivalent CCSEM analysis and use of the Ash Effect Predictor. The technique has been developed to take into account the impact of mineral-mineral association on ash properties. However the QEMSCAN technique and QEMSCAN data based mechanistic ash prediction models do require further development before the ash impact predictions are fully automated.

Background

Impacts of ash in power generation

Coals have a significantly content of ash-forming inorganic material with amounts commonly ranging between 10 and 25%. Ash impacts include those related to its collection, erosion, corrosion and ash deposition. This report has a primary emphasis on deposition with secondary emphasis on the other impacts.

Uncontrolled or unexpected deposits on the heat transfer surfaces in and around the boiler can interfere with operation, and cause unplanned shut-downs or reduced output and efficiency. The deposits are derived from the mineral matter in coal. They can be difficult to remove, and major incidents of internal damage due to fused ash material falling to the bottom of the boiler have occurred. The deposits interfere with heat transfer. With partial blockage between tube banks, increased gas velocities elsewhere are often associated with erosion. Corrosion may also occur underneath a developing deposit. All these factors affect the efficiency and availability of a plant for electricity generation and hence the power cost.(Couch 1994) Fine ash particles escaping from particulate matter capture equipment poses a major risk to environment.(Hinkley 2004).

Characteristics of ash

Ash is a heterogeneous material in which one ash particle differs from another in size, shape, chemistry, crystalline nature and other physical-chemical properties. Ash particles generally present a bio-modal particle size distribution, with coarse ash easily removed by particulate matter capture equipment while fine ash is difficult to capture. The shape of ash particles varies from spherical to angular, indicating differences in temperatures individual ash particles experienced and differences in melting behaviour of individual ash particles. Chemistry of individual ash particles can be close to stoichiometric compositions of pure minerals or of any possible combinations of different minerals. Some crystalline form ash particles can be identified while a glassy form is also prevalent.

Ash formation mechanisms

Transformation from mineral matter in coal to ash particles during combustion involves several physical and chemical processes including (1) coalescence of included mineral matter; (2) fragmentation of excluded mineral; (3) vaporization and condensation for fine ash formation; (4) cenosphere formation; (5) fusion of mineral matter. During combustion all these mechanisms simultaneously apply to mineral matter and change their size, shape, chemical composition.

Mineral matter in coal

Inorganic matter is the ash-forming material in coal. It can be present in crystalline mineral form, organically associated form and in the form dissolved in pore water in coal. In black coal, ash forming inorganic matter is dominantly in the form of mineral matter which has different chemical composition, size, shape and association. The occurrence of mineral matter determines ash properties which in turn determine ash impacts on combustion system. The complexity of mineral matter in coal poses a

great challenge to characterize and understand mineral matter in coal. Furthermore, the association of mineral matter has been less studied.

Thus in this project great effort has been taken to develop an advanced analytical tool for automated mineral characterization, with an emphasis on mineral associations.

Review of available analytical techniques for mineral matter characterisation with an emphasis on mineral associations

It has been established that pulverized coal is a heterogenous material and mineral compositions differ as a function of particle size and density. (Rayner and Marskell 1963) (Spears and Martinez-Tarazona 1993) Some conventional analytical tools such as optical microscope, scanning electron microscopy as well as advanced techniques such as CCSEM, XRD/SIROQUANT, Chemical fractionation have been reviewed and described below:

Optical microscopy: Examination of coal particles under optical microscopy and scanning electron microscopy shows that discrete mineral matter can be classified as either included mineral matter or excluded mineral matter. Optical methods for the identification and distribution of minerals in coals are based on detailed microscopic examination of polished or thin sections of coal in reflected or transmitted light. In principle, identification of a mineral type is made by observation. Quantitative analyses can be performed for specific minerals by counting techniques, but these methods are very tedious and are limited by the optical resolution of the microscope, which usually takes 1 micron as lower limit.

Scanning electron microscopy: Compared with optical microscopy, scanning electron microscopy can achieve much higher magnification (up to 20,000 times) and a great depth of focus (Wells, Royde et al. 1974; Goldstein 2003) so that submicron mineral grains can be identified which could not be identified by optical method. Equipped with wavelength or energy dispersive X-ray spectrometry, SEM can precisely positively identify minerals by their chemical composition. Mineral matter in coal had been studied with SEM by some investigators since 1970s. (Augustyn, Iley et al. 1976; Stanton and Finkelman 1979) When combined with petrographic analysis, association of minerals with specific macerals has been identified by SEM. (Finkelman and Stanton 1978)

X-ray diffraction (XRD): The measurement is based on diffraction of incident X-ray by crystalline structure of the minerals. The Bragg's law describes the interaction between interplanar spacing of crystals and incident X-ray:

$$n\lambda = 2d \sin \theta$$

where n is an integer, λ is the wavelength of the X-rays, d is the interplanar spacing generating the diffraction and θ is the diffraction angle, λ and d are measured in the same units, usually angstroms. X-ray diffraction (XRD) has been widely used for examination of the mineral matter in coals as reviewed. (Rao and Gluskoter 1973; Russell and Rimmer 1979; Renton 1986) It can be performed both qualitatively and quantitatively on low-temperature ash (LTA) and raw coal. Usually measurement made on LTA sample is better than that obtained on raw coal sample. Traditionally, an internal standard is required and the instrument is calibrated by mixtures of internal

standard and specific minerals of known composition. With Rietveld methodology, much more precise results can be obtained. (Rietveld 1969; Taylor 1991; Ward, Taylor et al. 2001) Siroquant, the software implementing Rietveld method has been widely used in Australia. (Ward, Taylor et al. 2001) Merits of XRD: (1) measurement does not affected by the grain size of minerals; (2) a large number of standard XRD traces are available for known composition crystalline minerals. Limits for XRD: (1) only crystalline phases in coal can be identified; (2) mineral transformation in low temperature ashing processes; (3) detection limits normally at about 1%; (4) factors like absorption characteristics, variation in mineral crystallinity, crystallite size, preferred orientation, matrix effects will reduce the degree of accuracy.

Infrared spectroscopy (IRS): IR method is based on measurement of optical radiation absorption bands from 650 to 200 cm^{-1} by the minerals. Briefly, the analysis is obtained from the successive subtraction the spectra of mineral standards from the spectrum of a mixture, usually the low-temperature ash (LTA) of the coal under investigation. (Painter, Coleman et al. 1978; Painter, Coleman et al. 1978; Painter, Snyder et al. 1980) The identification of major six or seven minerals including clay minerals, calcite, dolomite, quartz, and gypsum is successful and the measurement does not affected by poor crystallinity of some clay minerals and amorphous glass phases in ash. The detection limits of FTIR is about >3-4% for minerals in LTA samples and much lower for coal samples. But this method is not widely used for mineral identification.

Normative calculation: This method is not a direct measurement of minerals but a computation or inference based on assumptions concerning the mode of occurrence of different inorganic elements and the chemical compositions of the minerals. With some hints on the mineral matter in the sample, normative calculation can predict quite well results. This method provides a useful alternative for estimation of mineralogy. (Ward and Taylor 1996)

Thermal analysis: Some researchers have applied thermal analysis methods including differential thermal analysis (DTA), thermo gravimetric analysis (TGA) and differential thermo gravimetric (DTG) analyses in air, inert, or reducing atmosphere to the identification of minerals in coals. (Warne 1964; Watt 1968; Watt 1969; Warne 1970; O'Gorman and Walker 1971; O'Gorman and Walker 1973; Warne 1975)

Mossbauer Spectroscopy (MS): Mossbauer spectroscopy is a nuclear gamma ray technique based on the recoilless resonant absorption and emission of gamma rays by nuclei, a phenomena termed as Mossbauer effect. Because iron is one of most abundant elements in coal ^{57}Fe Mossbauer is commonly used for the determination the forms of iron in coal samples including iron sulphide, iron sulphates, iron carbonate and iron-bearing clays etc. With using iron Mossbauer, some iron-bearing minerals in coal and its derivative products have been studied. (Huffman and Huggins 1978) The same authors also used MS to study mechanism of weathering of pyrite to form iron sulphate and later to iron oxyhydroxides has been found for some U.S. coals. (Huggins, Huffman et al. 1987)

Computer Controlled Scanning Electron Microscopy (CCSEM): CCSEM is capable of automatically characterizing minerals in term of size, shape, abundance and associations. A CCSEM usually consists of a SEM, an energy dispersive X-ray

spectrometer (EDS) and a controlling software program. The scientific foundation of a CCSEM is interaction between an incident high-energy electron beam and the coal sample specimen. Signals generated such as secondary electrons, backscattered electrons and characteristic X-ray photons are collected by different detectors, and interaction of movement of electron beam and signal measurement is controlled by computer software. CCSEM identifies the elemental composition of a mineral grain and deduce its mineral type. The mineralogy reported for a coal sample is based on several thousands mineral grains. In CCSEM technique, it mainly consists of five major components as shown in a prototype by White (White, Mayberry et al. 1972): (1) Sample preparation: ground particles of coal are mounted and polished in an epoxy resin; (2) Mineral location: mineral grains are determined in the polished section of coal on the basis of their brightness in the back-scattered electron image which is a function of average atomic number; (3) Compositional analysis: in this system, when mineral grains are located, they are sized by their cross-sectional area and their elemental compositions are determined by monitoring several x-ray channels by EDX. From the various combinations of relative X-ray intensities of these elements, it is possible to identify most of the commonly occurring minerals in coals; (4) Statistical consideration: in a typical run, as many as 2000 particles are examined for their composition and size; (5) Data output: after the data are recorded, the computer presents the results in a summary file, which lists average size, size distribution, shape factor, volume and number percentages for each mineral type; (6) Limitations: for quantitative analysis the method can be applied only to mineral grains larger than about 1 micron in diameter because it is limited by the lower limit of resolution of the x-ray system.

All the CCSEMs operate in a similar procedure as designed by White. But due to some variation in development of hardware of CCSEM including detector type (low atomic element detector/ common detector), detector window (thick window/ thin window/ windowless) and operating conditions (e.g. accelerating voltage, working distance, single point measurement/grid measurement), each instrument uses a different mineral classification or definition scheme to deduce mineral types from the EDX analysis. As a result of variation in hardware and software data reported from different CCSEM instrument varies. This makes it is difficult to compare analysis results from different CCSEM.

CCSEM techniques for addressing the problem of the determination of mineral-organic association were first described by Straszheim and Markuszewski at Iowa State University (Straszheim, 1990A, 1990B, 1992). Wigley and Williamson (1997) also determined mineral-organic association and applied the results to combustion problems. EERC also developed the concepts of included mineral grains and excluded mineral grains for coal combustion application. At Brigham Young University the CCSEM technique has been used to examine both mineral-organic association and mineral-mineral associations in pulverized coal (Yu, Marchek et al. 1993).

QEMSCAN: In Australia, a new analytical technique to characterize the mineral matter in coal particles, based on a technique similar CCSEM, called QEM*SEM was developed by CSIRO some years ago (Gottlieb, 1990; Creelman 1996). QEMSCAN is the latest product in the QEM*SEM family and is an automated image analysis system that uses Backscattered Electron (BSE) and Energy Dispersive X-ray (EDX) signals from a Scanning Electron Microscope (SEM) to create digital images in which

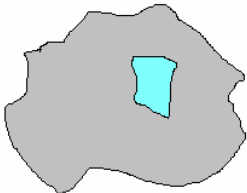
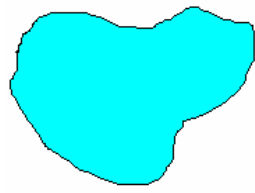
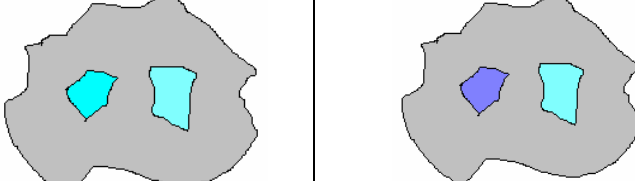
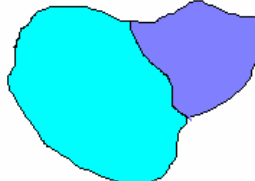
each pixel corresponds to mineral species in a small region under the electron beam. Once an individual particle section has been located from BSE image, it is scanned by a grid of points and the backscattered electrons and the Energy Dispersive x-ray (EDX) photons emanating from a given point are used to identify the elements present and thus classify the mineral species present. The image of the particle sections is built up pixel-by-pixel in this manner. Each pixel in each particle section image is assigned a number, which is a unique identifier of the species at that point in the section using Species Identification Program (SIP). A unique feature of QEMSCAN is the light element detectors which have been installed and that can measure elements with atomic number down to carbon. With the development of QEMSCAN it is now feasible to study mineral-organic and mineral-mineral associations on a pixel-by-pixel basis. (Liu, Gupta et al. 2005)

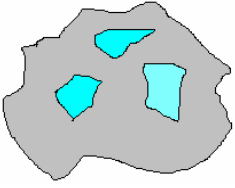

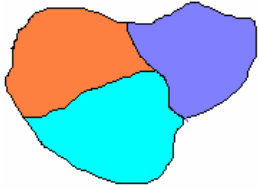
Coal mineral and mineral-mineral associations in pf

According to its association with coal matrix, a mineral grain can be classified as included or excluded. Included mineral matter refers to those discrete mineral grains that are surrounded by the carbon matrix. Excluded minerals are those discrete minerals not associated with coal carbonaceous matter. The distribution of mineral grains between included minerals and excluded minerals are strongly affected by milling operation. During milling, a large number of mineral grains are liberated from the coal matrix to form excluded mineral grains. The proportion of included minerals in coal decreases with enhanced pulverization, particularly for larger mineral grains locked within the carbon matrix. In pulverized coal, the amount of excluded mineral increases with increased grinding.

The mineral-mineral associations refer to existence of several mineral phases in a single particle. For an excluded mineral grain, mineral-mineral association refers to more than two mineral phases in the same grain; for an included mineral grain, mineral-mineral association refers to several included mineral grains in the same single coal particle. The concepts of coal-mineral association and mineral-mineral association are graphically illustrated below:

Table 1: Generic classification of mineral-mineral associations

Associations between included mineral grains	Associations between excluded mineral grains
	
(a) One included mineral grain in a coal particle	(b) One single phase excluded mineral grain
	

(c) Two included mineral grains of the same type in one coal particle	(d) Two included mineral grains of different types exist in one coal particle	(e) Two mineral phases in one excluded mineral grain
		
(f) Three included mineral grains of the same type in one coal particle	(g) Three included mineral grains of different type in one coal particle	(h) Three mineral phases in one excluded mineral grain

The distribution between excluded mineral and included mineral grain determines their transformation during combustion because this determines the chemical composition of the resulting ash and the particles have different temperature-time history. Generally one included mineral grain exposed to a higher particle temperature and stronger reducing atmosphere in comparison with an excluded mineral grain.

The mineral-mineral association determines the possibilities of several mineral grains reacting with each other to form a chemical mixture of different melting behaviour. Mineral associations in excluded mineral grains make such interactions straightforward because of physical proximity of the mineral phases. However mineral associations in included mineral grains are not the solely factor determining their interaction or coalescence behaviour because of potential char formation and fragmentation.

Comparison of techniques

From the above, we can conclude that the association of mineral matter in coal can be classified at two levels, i.e., on the whole pulverized coal sample and on the single coal particle basis. Density fractionation and size fractionation methods provide a feasible way to study mineral distribution in the whole pulverized coal sample. With a pre-separation, minerals in each fraction then can be characterized and studied by using XRD, SEM, Optical method or FTIR method to provide insight into the distribution of minerals into different parts of coal sample. In the other hand, microscopy and scanning electron microscopy based methods with chemical fractionation provides information of association of inorganic elements on a single coal particle and molecular level. OM, SEM, CCSEM and QEMSCAN analyze coal particles directly on cross section of a sample without previous separation of mineral matter from inorganic matter. Thus they avoid all the problems encountered during separation of MM from IM by size fractionation, density fractionation and chemical fractionation. The only issue in this type of technique is estimating the true association from the two-dimensional analysis, lack of information on organically associated mineral grains and limits of mineral grain size. Chemical fractionation method usually characterizes the inorganic matter associated with organic matter by differences in ionic bonding on a molecular level. This method may modify the inorganic matter and form artificial minerals. Quantitative analysis is still problematic. As the study subjects are mainly black coals in Australia, in which discrete mineral

grains account for a much higher fraction of the total inorganic matter, thus the determination of mineral grains distribution with CCSEM technique is the most suitable tool. And QEMSCAN is the only instrument can provide information on mineral-mineral associations and how minerals associate in a single coal particle and in an excluded mineral grain.

Table 2: A comparison on various mineral characterization techniques applied to pf

	Principals of mineralogy analysis	Size and shape	Association
Optical microscopy	Determined by point counting technique, operated manually	Can be determined under image	Coal-mineral association can be observed under image
Scanning electron microscopy	Similar to optical microscopy	Similar to optical microscopy, with a higher magnification	Similar to optical microscopy
XRD	Determination of the crystalline phase in coal	Not available	Not available
Infrared spectroscopy	Determination from molecular radiation absorption	Not available	Not available
Normative calculation	Inferred from chemistry analysis	Not available	Not available
Thermal analysis	Determined by thermal behaviour of minerals	Not available	Not available
Mossbauer spectroscopy	Determined on Mossbauer effect	Not available	Not available
CCSEM	Determined by EDS or WDS analysis	Automated and determined	Coal-mineral association is available
QEMSCAN	Similar to CCSEM	Automated and determined	Coal-mineral association and mineral-mineral association are available

QEMSCAN status

Analytical status: The current status of QEMSCAN is that it has been calibrated for several major commonly occurring minerals in coal, however if there is a unusual mineral present in the sample it needs further calibration; furthermore some current mineral species may need refinement if natural occurring minerals have chemical

composition significantly differing from theoretical stoichiometric composition; interpretation of QEMSCAN data requires expertise knowledge in corresponding fields.

Interpretation of QEMSCAN analysis: There are principally three major ways to apply QEMSCAN data to ash impacts issues in power stations as described below:

1 Observation of QEMSCAN images: Intellection Pty Ltd, the maker of QEMSCAN, recently released a new data analytical software iDiscover™ 4.1 in which it is capable of observing individual mineral grains and generating statistical graphs or tables to allow comparison between coals and infer impacts.

2. Ash formation prediction after conversion to equivalent CCSEM analysis: A software interface was developed by CCSD to convert QEMSCAN image based data into a CCSEM-like text based data forma. Thus QEMSCAN data can be interpreted with ash formation model formerly developed at the University of Newcastle. The application of such conversion technique can be found elsewhere, and allows QEMSCAN analysis to be used in the CCSD Ash Effect Predictor (AEP) (Liu, Gupta et al. 2005) However, with this conversion technique, some information provided by QEMSCAN such as mineral-mineral association is lost.

3. Ash formation prediction directly from QEMSCAN analysis: This technique has been developed to take into account the impact of mineral-mineral association on ash properties. Detailed information can be found elsewhere.(Liu, Gupta et al. 2005) With the update in iDiscover™ this technique also needs further development to incorporate detailed ash formation mechanisms and is not currently in the AEP.

Conclusions and recommendations

For pulverized coal utilization, the QEMSCAN technique is the state-of-the-art advanced mineral characterization technique capable of providing size, shape, abundance and associations of mineral matter in coal.

Currently QEMSCAN analysis can be interpreted to predict ash impacts in pf furnaces by two methods, observation of QEMSCAN images and comparison of coals by statistical means and prediction after conversion to an equivalent CCSEM analysis and use of the Ash Effect Predictor.

The technique has been developed to take into account the impact of mineral-mineral association on ash properties. However the QEMSCAN technique and QEMSCAN data based mechanistic ash prediction models do require further development before the ash impact predictions are fully automated.

References: (Here, references to papers referred to in the text are given together with other significant papers on mineral analysis and ash)

Augustyn, D., M. Iley, et al. (1976). Optical and scanning electron microscope study of brown coals. *Fuel* **55**(1): 25-38.

Couch, G. (1994). *Understanding Slagging and Fouling During Pf Combustion*. London, IEA Coal Research: 118.

Finkelman, R. B. and R. W. Stanton (1978). Identification and significance of accessory minerals from a bituminous coal. *Fuel* **57**: 763.

Goldstein, J. I. (2003). *Scanning electron microscopy and x-ray microanalysis*. New York, Kluwer Academic/Plenum.

Hinkley, J. T. (2004). *the Contribution to atmospheric particulates of ash emitted from coal fired power stations*. Chemical Engineering. Newcastle, the University of Newcastle: 166.

Huffman, G. P. and F. E. Huggins (1978). Mossbauer studies of coal and coke: quantitative phase identification and direct determination of pyritic and iron sulphide sulphur content. *Fuel* **57**(10): 592-604.

Huggins, F. E., G. P. Huffman, et al. (1987). Low-temperature oxidation of bituminous coal: Its detection and effect on coal conversion. *Fuel Processing Technology* **15**: 233-244.

Liu, Y., R. Gupta, et al. (2005). Mineral matter-organic matter association characterisation by QEMSCAN and applications in coal utilisation. *Fuel* **84**: 1259-1267.

Liu, Y., R. Gupta, et al. (2005). Mineral-mineral associations in pulverized Australian coals. 5th Asian Pacific Conference on Combustion, Adelaide, Australia.

O'Gorman, J. V. and J. Walker, P. L. (1971). Mineral matter characteristics of some American coals. *Fuel* **50**(2): 135-151.

O'Gorman, J. V. and J. Walker, P. L. (1973). Thermal behaviour of mineral fractions separated from selected American coals. *Fuel* **52**(1): 71-79.

Painter, P. C., M. M. Coleman, et al. (1978). Fourier transform infrared study of acid-demineralized coal. *FUEL* **57**.

Painter, P. C., M. M. Coleman, et al. (1978). Fourier Transform Infrared study of mineral matter in coal. A novel method for quantitative mineralogical analysis. *Fuel* **57**: 337-344.

Painter, P. C., R. W. Snyder, et al. (1980). Analysis of kaolinite in coal by infrared spectroscopy. *Fuel* **59**: 364-366.

- Rao, C. P. and H. J. Gluskoter (1973). Occurrence and distribution of minerals in Illinois coals. Illinois State geological Survey, Circular **476**.
- Rayner, J. E. and W. G. Marskell (1963). The distribution of mineral matter in pulverized fuel and solid products of combustion. Conf. Mechanism of Corrosion by Fuel Impurities, Marchwood, U.K., Butterworth, London.
- Renton, J. J. (1986). Semiquantitative determination of coal minerals by X-ray diffractometry. Mineral matter and ash in coal. K. S. Vorres. Washington, DC, American Chemical Society: 53-60.
- Rietveld, H. M. (1969). A Profile Refinement Method for Nuclear and Magnetic Structures. *A. Appl. Cryst* **2**: 65-71.
- Russell, S. J. and S. M. Rimmer (1979). Analysis of mineral matter in coal, coal gasification ash, and coal liquefaction residues by scanning electron microscopy and x-ray diffraction. *Analytical Methods for Coal and Coal Products*. C. J. Karr. New York, NY, USA, Academic Press. **III**: 133-162.
- Spears, D. A. and M. R. Martinez-Tarazona (1993). Geochemical and mineralogical characteristics of a power station feed-coal, Eggborough, England. *International Journal of Coal Geology* **22**(1): 1-20.
- Stanton, R. W. and R. B. Finkelman (1979). Petrographic analysis of bituminous coal: optical and SEM identification of constituents. *Scanning Electron Microscopy* **1**: 465-472.
- Taylor, J. C. (1991). Computer programs for standardless quantitative analysis of minerals using the full powder diffraction profile. *Powder Diffraction* **6**: 279.
- Ward, C. R. and J. C. Taylor (1996). Quantitative mineralogical analysis of coals from the Callide Basin, Queensland, Australia using X-ray diffractometry and normative interpretation. *International Journal of Coal Geology* **30**: 211-229.
- Ward, C. R., J. C. Taylor, et al. (2001). Quantification of mineral matter in the Argonne Premium Coals using interactive Rietveld-based X-ray diffraction. *International Journal of Coal Geology* **46**: 67-72.
- Warne, S. S., J. (1964). *J. Inst. Fuel* **38**(292): 202-217.
- Warne, S. S., J. (1970). *J. Inst. Fuel* **43**(292): 240-242.
- Warne, S. S., J. (1975). An improved differential thermal analysis method for the identification of calcite, dolomite and ankerite in coal. *J. Inst. Fuel* **50**: 142-145.
- Watt, J. D. (1968). The physical and chemical behaviour of the mineral matter in coal under conditions met in combustion plant. Part 1, The occurrence, origin, identity, distribution, and estimation of the mineral species in British coals.

Leatherhead, Surrey, England, BCURA, National Coal Board,
Cheltenham,U.K.

Watt, J. D. (1969). The physical and chemical behaviour of the mineral matter in coal under conditions met in combustion plant. Part 2. Leatherhead, Surrey, England, BCURA, National Coal Board, Cheltenham,U.K.

Wells, O. C., A. Royde, et al. (1974). Scanning electron microscopy. New York, McGraw-Hill.

White, E. W., K. Mayberry, et al. (1972). Computer analysis of multi-channel SEM and X-ray images from fine particles. *Pattern Recognition* 4: 173-192.

Yu, H., J. E. Marchek, et al. (1993). Characterisation of minerals and coal/mineral association in pulverized coal. Proceedings of the Engineering Foundation Conference, St. John's Swallow Hotel, Solihull, England, Taylor and Francis, Washington.